

Laminar Flow Supersonic Wind Tunnel

Primary Air Injector

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Abstract

This paper describes the requirements, design, and prototype testing of the Flex-Section and Hinge Seals for the Laminar Flow Supersonic Wind Tunnel Primary Injector. The supersonic atmospheric Primary Injector operates between Mach 1.8 and Mach 2.2 with mass-flow rates of 62 to 128 lbm/s providing the necessary pressure reduction to operate the tunnel in the desired Reynolds number (Re) range.

Introduction

Research in supersonic flow has been reawakened with the recent interest in the commercial supersonic transports such as the High Speed Civil Transport (HSCT). Creating low-disturbance, laminar flow at supersonic speeds inside a wind tunnel has been elusive. The Laminar Flow Supersonic Wind Tunnel (LFSWT) at NASA-Ames Research Center will support supersonic laminar flow control research using a radically new design approach. Most wind tunnels, regardless of speed have either a blow-down or recirculating configuration. Blow-down tunnels are normally limited by the supply volume of compressed air. Recirculating supersonic wind tunnels are usually pressurized and require heat exchangers to remove the adiabatic-compression-temperature rise during each circuit. In addition, temporal and spatial turbulence is also a problem.

The LFSWT at NASA-Ames Research Center is a radical departure from existing wind tunnel designs. The LFSWT is a continuously operating, quiet flow, supersonic wind tunnel utilizing a nonspecific centrifugal compressor, settling chamber, nozzle, test section, two atmospheric air injectors, and the Center's existing 207 bar (3000 psi) air system (Figure 1). Most supersonic wind tunnels operate at higher than atmospheric

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pressure and all are “noisy” or high disturbance wind tunnels. Quiet supersonic wind tunnels are defined as tunnels with pressure fluctuations of 0.05% or less in the test core.¹ Wind tunnels are described by the size of the test section. The LFSWT is 20.32 cm (8 in.) high by 40.64 cm (16 in) wide. Mass-flow rates for the test section range up to 9.52 kg/s (20 lbm/s) with speeds ranging from Mach 1.6 to Mach 2.5. Reynolds numbers (Re) will range from one million to five million. To achieve the low end of the desired Re , the tunnel stagnation or total pressure (P_O) must be below the minimum exit pressure (P_E) at the throat. The stagnation pressure is the pressure created by bringing the flow to rest isentropically. This means the LFSWT must operate with a compression ratio uniquely less than unity (P_O/P_E down to 0.6251 with $Re=1$ million per foot at $P_O = 0.34$ bar (5 psia)).¹ To achieve a lower stagnation pressure than the capability of the compressor, two supersonic air injectors were utilized down stream of the test section. Taking advantage of extremely high mass-flow capability of the compressor (much higher than the 20 lbm/s required from the test section), two full-scale, supersonic ambient air injectors, Primary and Secondary, are used in the LFSWT. Supersonic air injectors create jets of low pressure, high energy air downstream of the test section. Air injectors are designed in pairs, opposite of one another. The low pressure created downstream reduces the Reynolds number and test section exit pressure into the desired range. Thus, by using two air injectors, the tunnel operates at lower pressure than the downstream indraft air compressor is capable of achieving. The first injector has a variable mass-flow and mach number. The second injector has a fixed geometry, a constant mass-flow of 95.2 kg/s (200 lbm/s), and an exit of Mach 2.0.

This paper will address the unique design requirements, full scale prototype development, and consequent design solutions for the Primary Injector (Figure 2).

The Primary injector is composed of two pairs of four moving component sub-assemblies; the Slider Assembly, the Flex-Section, the Contoured Throat Plate, and the Hinge Plate. The Contoured Throat Plate is actuated

by two sets of ball screws. One set of hand-operated ball screws controls the injector nozzle throat and the other set actuates the nozzle exit. Each ball screw set can be moved independently of the other. Moving the throat ball screw set varies the mass-flow rate through the nozzle. Moving the nozzle exit ball-screw set varies the exit velocity. The system was designed to be infinitely adjustable and to be repeatable within the design criteria described below. Infinite adjustment required that only one end of the mechanism assembly be fixed. The exit end of the Hinge Plate is attached to the tunnel side walls via an 88,960 N (20,000 lbf) radial capacity hinge. As the Contoured Throat Plate is positioned from maximum mass-flow rate and Mach number to the minimum mass-flow rate and Mach number, the Hinge Plate oscillates through $\pm 20^\circ$. The Flex-Section is fixed to both the Contour Throat Plate and the Slider Assembly. The Slider Assembly allows only longitudinal motion and has a low pressure, sliding seal. When changing the nozzle and exit positions of the Primary Injector, the Contour Throat Plate moves longitudinally and rotates simultaneously. The Flex-Section and Slider Assembly combine to form a flexible, continuous duct through out all design parameters.

Overall Design Parameters

Speeds in the Primary Injector nozzle range from Mach 1.8 to Mach 2.2 while the injected mass-flow range changes from 30.46 kg/s to 60.92 kg/s (64 lbm/s to 128 lbm/s). Inside the injector and mixing region, the flow is unstable and, consequently, structural vibrations are high. Nozzle and exit geometries must be repeatable to within 0.136 mm (0.005 in). To insure accurate and repeatable measurements of the throat and exit geometries, optical encoders coupled to eight (four each side) zero-backlash ball screws are used for positioning. External pressure loads range from 0.136 bar (2 psia) at the two inlets to 0.92 bar (13.5 psia) in the mixing region. Due to the low internal pressure, all hinge and flex joints and sliding plates must be leak-tight and maintenance free in all positions. Slight leaks perpendicular to the flow will severely decrease injector performance. Pressure loads created during operation deflect the 50.8 mm (2 in.) thick Side-Walls so that moving the Contour Throat Plate is

not possible. The structure required for throat and exit adjustment during operation was not feasible.

Sealing Requirements

To seal the sides of the Slider Assembly, Flex-Section, Contour Throat Section and Hinge Plate a continuous, longitudinal, 1/4 nominal, buna-N O-ring was used on each side. A simple sliding motion study determined that the O-ring would not fail by twisting longitudinally inside the O-ring gland during repositioning (Figure 3).

Design/Prototype Development

Development and prototype testing concentrated on the Flex-Section and the Hinge Joints. The Flex-Section is between the Slider Assembly and the Contour Throat Plate. The hinge joints are between the Contour Throat Plate and the Hinge Plate and between the Hinge Plate and Bridge Plate.

Flex-Section Development

The Flex-Section Prototype was made from 0.81 mm (0.032 in) thick C1095 spring steel and a medium viscosity, adjustable durometer polyurethane (Figure 4). The urethane was cast to the spring steel to form a O-ring gland for the longitudinal O-ring seal. Speeds in the Flex-Section begin at Mach 0.3 and terminate at Mach 0.8 just before critical flow in the Contour Throat Plate. Bend testing of the prototype far beyond the operating range of motion yielded no problems. Two changes were made to the final design. First, the O-ring gland was moved downward until the bottom of the O-ring gland was formed by the spring steel. Urethane formed the other two sides. For the second modification, a 6.3 mm (0.25 in.) layer of polyurethane was bonded to the back side of the spring steel to dampen and lowered the spring steel's natural frequency (Figure 5).

Hinge Seal Development

Two zero-leak hinge joints are required. Each hinge joint must seal across the axis of hinge motion and seal longitudinally, using the linear O-ring seal. The range of motion for the hinge is $\pm 20^\circ$ past center.

Three hinge concepts were tested and two failed. As with many great ideas, the translation from the concept/design phase to the testing phase was not always satisfactory.

Hinge Concept No. 1

The initial series of three prototypes only used the polyurethane rubber to form the flexible hinge section (Figure 6). (This idea is similar to the living hinges on plastic cases). If this concept had worked an O-ring gland for the longitudinal O-ring would have been cast into the hinge. Two of the prototypes had a triangular hinge joint design. The angle was determined by the maximum combined stress from the shear and tensile properties of the polyurethane material. Spacing between the metal parts was varied to determine the joint shear strength versus bending resistance. The third prototype had two straight joints perpendicular to the flow surface.

Test Results

Bending tests were performed using the Material Test System MTS 810 and Graphtec X Y Recorder. Force versus deflection graphs were plotted. The joint deflection was limited to 20 degrees. The first and second prototypes delaminated around the tip of the radiused triangle. Delamination and tears in the material were caused by strain over too little material. The third prototypes did not fail visibly, however the material continued to relax with sustained loading. Internally, the molecular bonds were breaking and would eventually fail, similar to an old rubber band. Shear tests on the joints were not performed.

Hinge Concept No 2.

The second series of prototypes was a combination of two ideas. A mechanical hinge on the top of the joint would eliminate the shear and some tensile loading from the polyurethane hinge seal. Since seal strength, other than pressure loading, was not important, three more hinge prototypes were fabricated with 60 durometer (softer) polyurethane instead of the 80 durometer polyurethane used in the first series (Figure 7). Installing the hinge on the top of the joint forced the seal to stretch outside the neutral axis of the seal. The trapezoidal seal shape was defined by a line from the center point of hinge action to the sealing edge. Calculations based on the allowable strain for the polyurethane determined the joint angle. To reduce the tensile forces required to open the hinge and compression forces required to close the hinge, two composite hinge seals were fabricated. The third seal was solid polyurethane. The Contoured Throat Plate and Hinge Plate material was changed from A-36 steel to 6061-T6 aluminum to reduce part machining time. The first prototype contained trapezoidal foam cores, each 3 inches long. Between the soft foam cores, a solid 12.7 mm (0.5 in.) rib of urethane material remained. The trapezoidal foam cores were smaller than the joint and surrounded by a 9.5 mm (0.375 in) thick urethane layer. The ribs helped restrain the thin seal membrane from folding into the air flow when the hinge joint was closed. The foam also helped reduce the actuation forces during operation. The second prototype contained seven, 9.5 mm (0.375 in.) diameter, 30 durometer, closed cell, neoprene cords strung laterally along the joint in a trapezoidal formation. Again the softer material reduced the actuation forces and stress on the joint during fabrication. The last prototype was solid, 60 durometer polyurethane. Each sample was oven cured to full strength before testing.

Test Results

The most promising design, the trapezoidal foam core prototype was tested first. Again the MTS 810 and graphic recorder test apparatus was used and the same parameters of force versus deflection were plotted. The

prototype delaminated along the outer flow side. However, the foam core concept seemed to restrain the flow-side membrane from popping out into the air flow when the joint was compressed during closing. The second, neoprene cored prototype did not delaminate. Actuation forces were not excessive. However it was the second prototype that called to our attention another design flaw. Because of the off-center hinge point, the strain in the bottom fibers was the highest. This caused the bottom corners of the seal to draw inward, away from the longitudinal O-ring seal on the side walls. This effect was created by a volumetric, (Poisson's) contraction due to the strain in the bottom fibers. The third, solid prototype failed at both the joint and in the middle of the seal. In all three cases, the stresses and strains were well within the manufacturer's recommendations. If the polyurethane hinge seal was to be used, the maximum strain had to be no more than 25 percent of the strains we tested.

More Design Concepts

Three more design concepts were considered. In each we tried to overcome the limitations of the material and meet the design criteria of 20° in each direction. The design concepts became more and more complicated requiring more prototype testing.

Final Design

The final design was a radical departure from the previously described hinge seals. Prototype testing of the Flex Plate inspired a similar design approach for the hinge seals (Figure 8). Two U-shaped pieces of stainless steel sheet with cast O-ring glands provided the sealing around both hinges. The hinge design was mechanically limited by the amount of travel in the downward position. The upward rotation was not directly limited, however, the seal sheet could only withstand so much rotation without permanent deformation. The sheet thickness was a compromise between buckling strength and bending stress. To eliminate the large bending stresses, the sheets were rolled to the average bend radius, thus dividing the required deflection. This modification did, however,

complicate the mold required to cast the polyurethane O-ring gland onto the sheet. To confirm the seal design and the influence of the polyurethane on buckling strength, a Patran/Nastran computer analysis was performed. The buckling strength was only increased by 2 psi with the polyurethane added.

Conclusion

The final design of the key sealing areas in the Primary Injector included three flexible composite seals. Each seal had an O-ring gland cast into each side to provide longitudinal sealing of moving parts. All parts are in fabrication at this time. The first test will be an F-16XL Aircraft wing in support of the Supersonic Laminar Flow Control (SLFC) studies.

Lessons Learned

- 1) Keep the design simple.
- 2) If you have a novel solution to a unique problem, test it first.
- 3) Simple models can be made to test and confirm ideas.
- 4) If your solution doesn't work the first time, don't take it too seriously. (Don't give up!!)
- 5) Keep the project in perspective.

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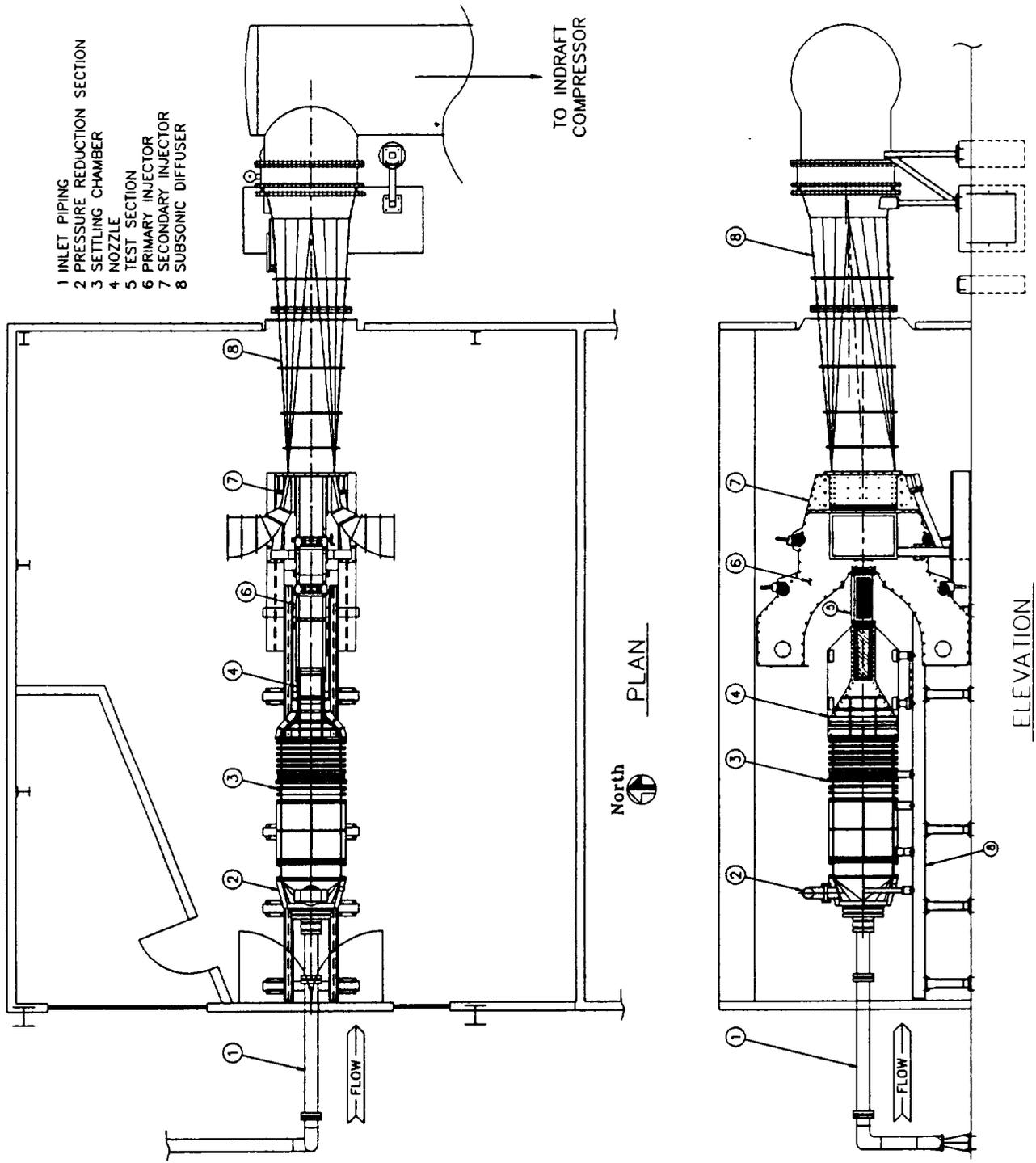


Figure 1. Laminar Flow Supersonic Wind Tunnel (LFSWT)

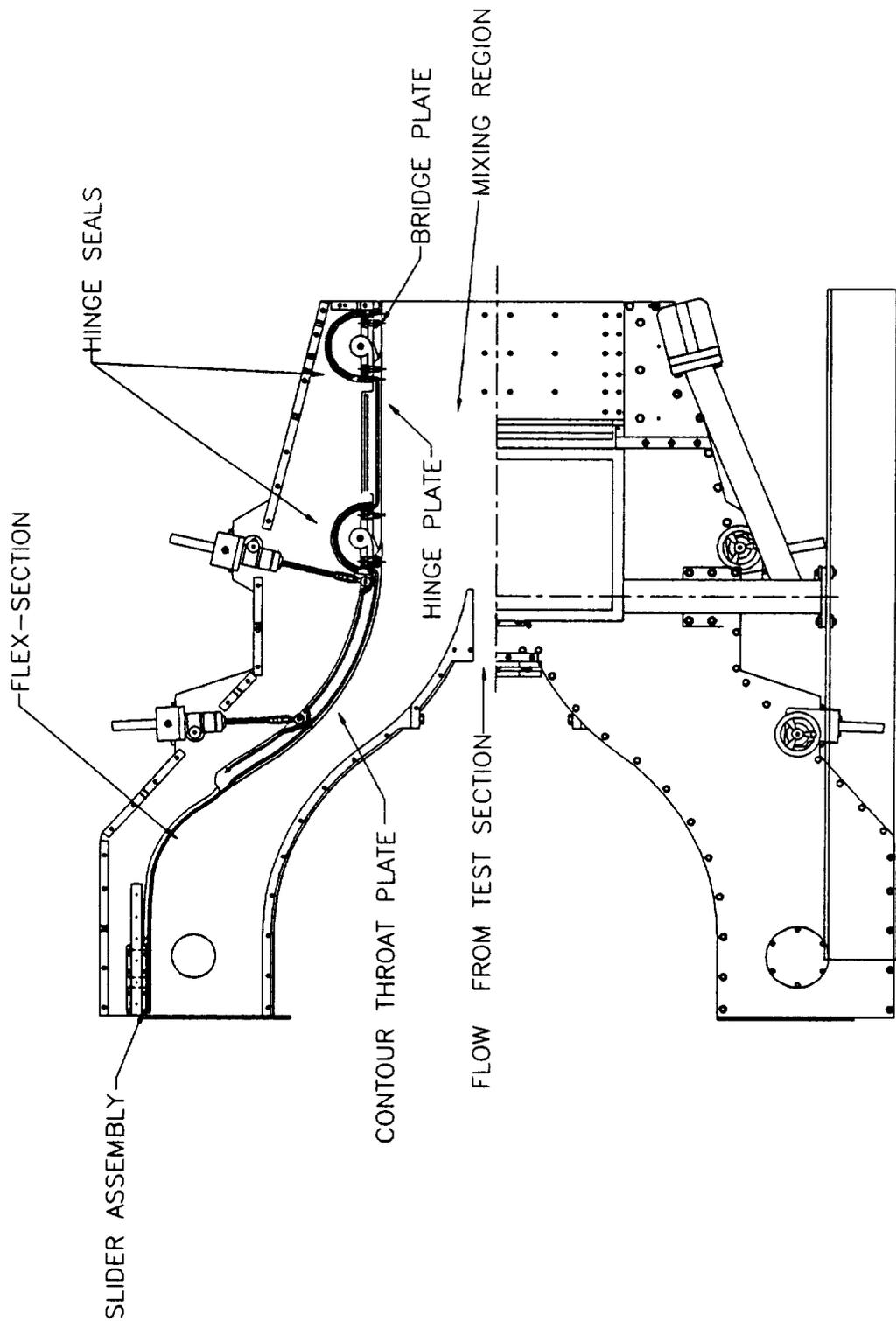


Figure 2. Primary Injector

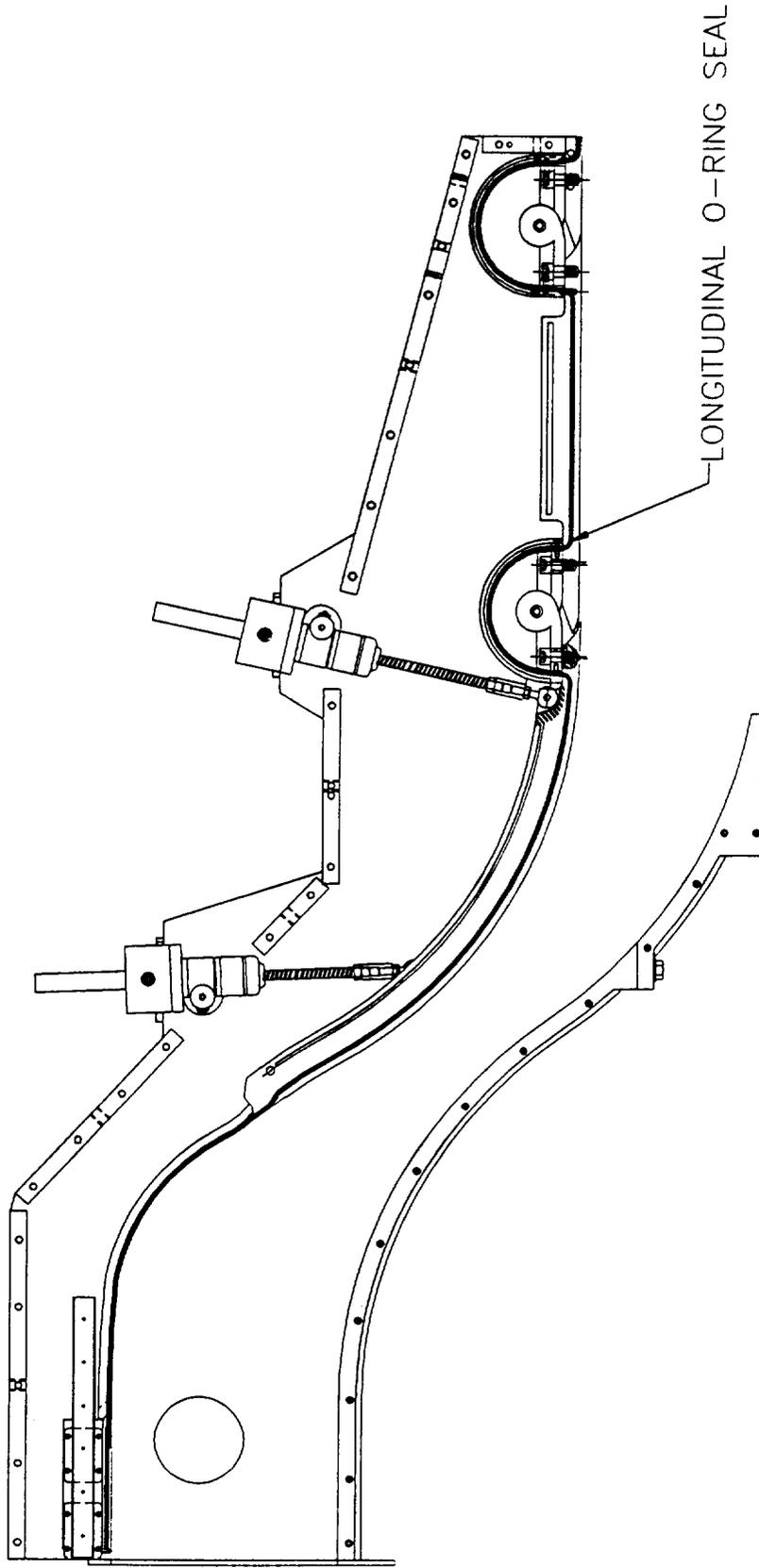


Figure 3. Longitudinal O-Ring Seal

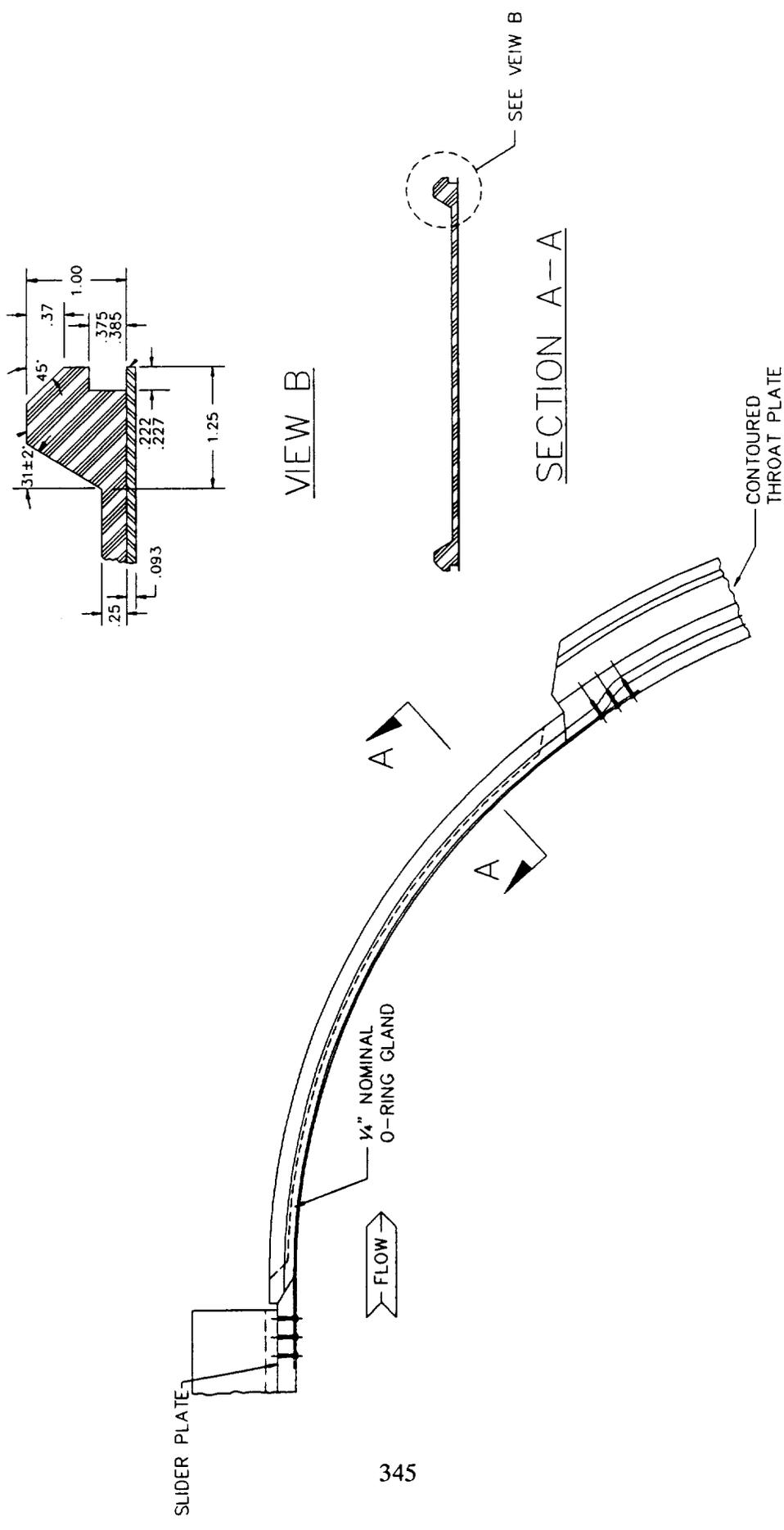
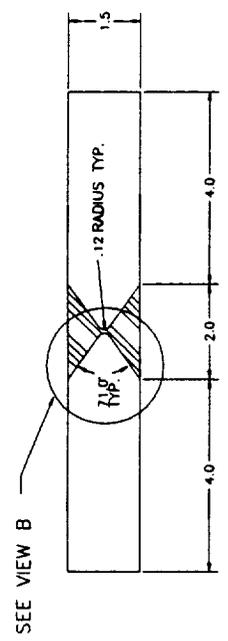
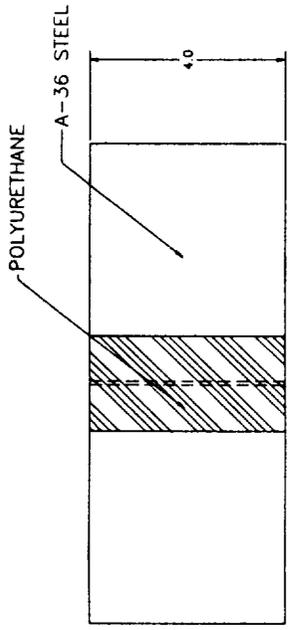
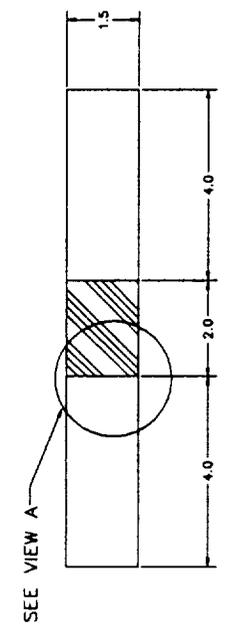
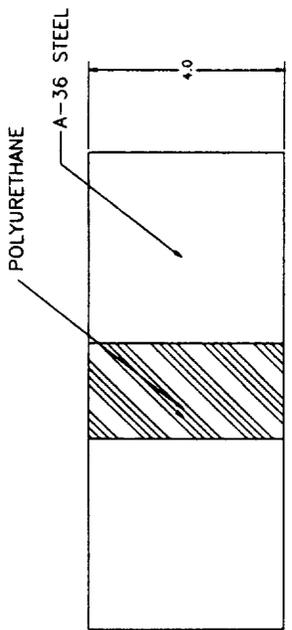


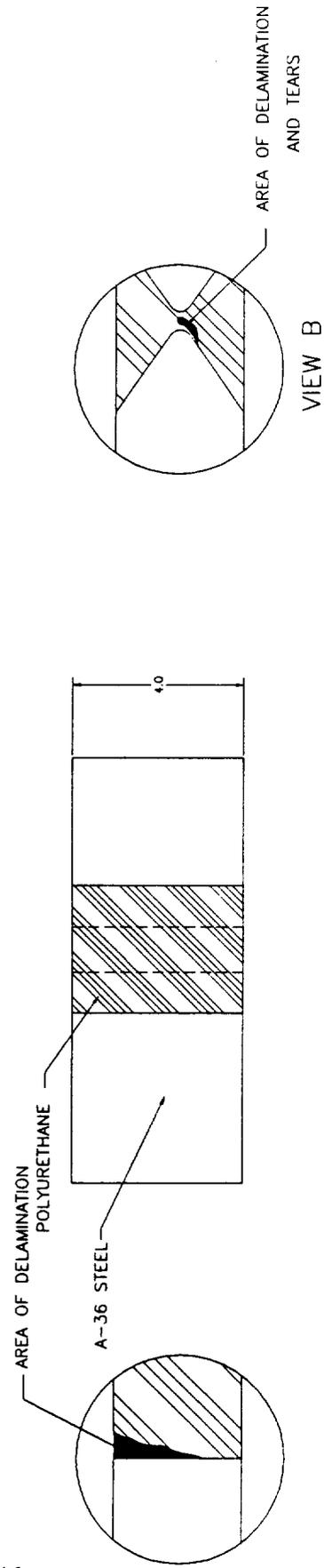
Figure 5. Flex-Section Final Design



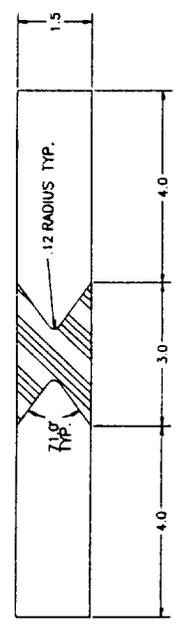
PROTOTYPE NO. 2



PROTOTYPE NO. 3



PROTOTYPE NO. 1



VIEW A

Figure 6. Hinge Concept No. 1

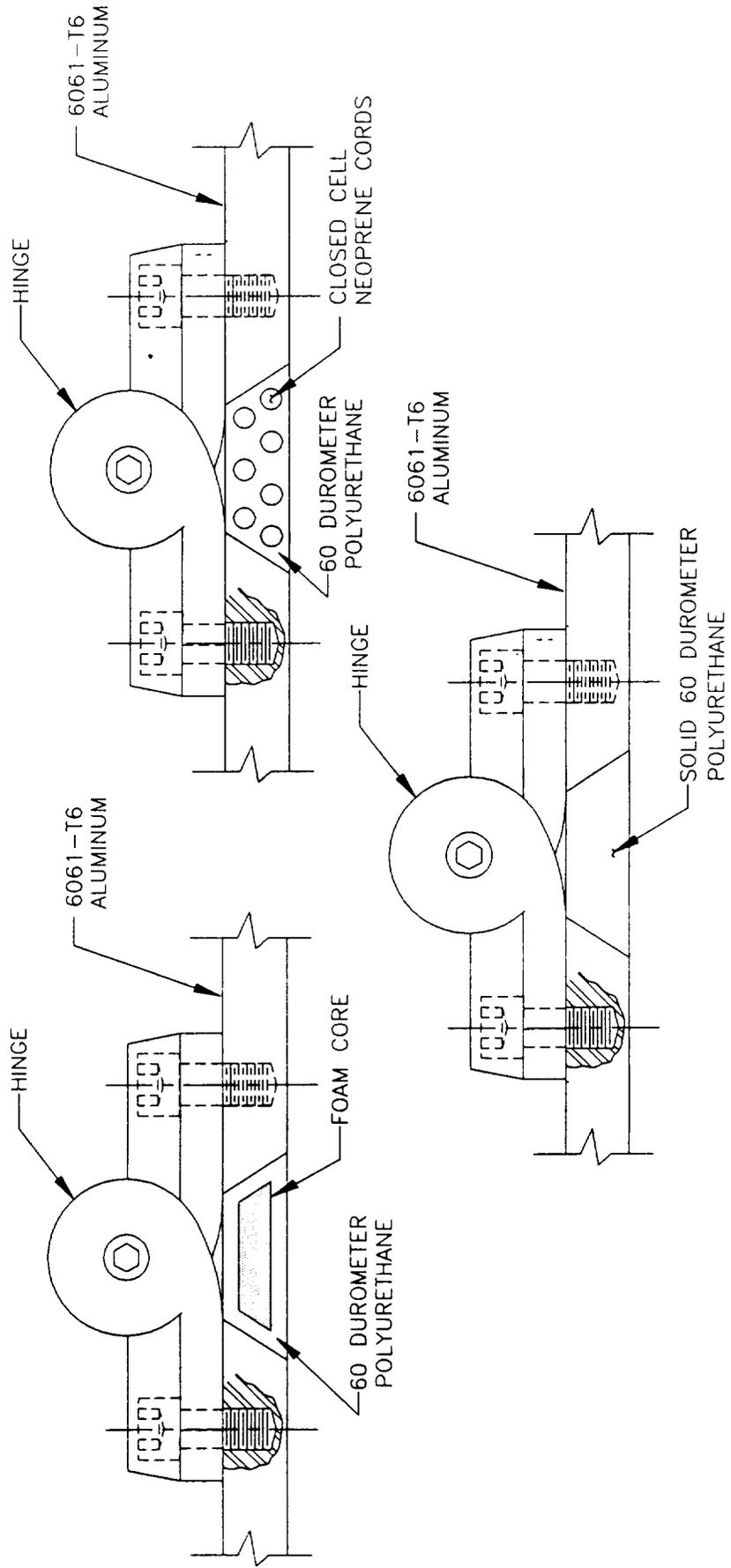


Figure 7. HINGE CONCEPT NO. 2

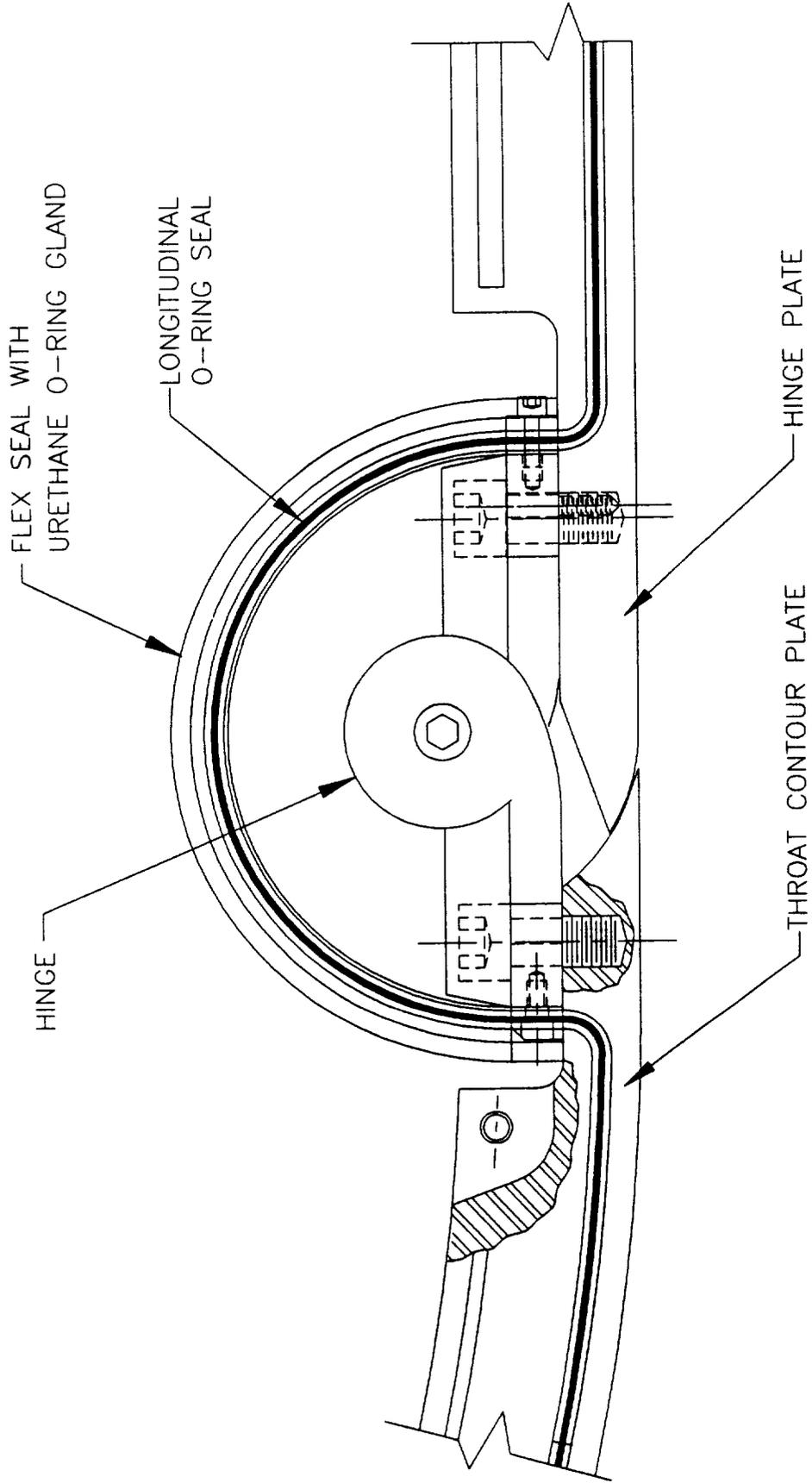


Figure 8. FINAL HINGE SEAL DESIGN